RI 9163

Bureau of Mines Report of Investigations/1988

Measurement and Control in Industrial Processes Using an Analog-to-Digital Telemetry System

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

McDonough, P. J. (Patrick J.)
Measurement and control in industrial processes using an analog-to-digital telemetry system.

(Report of investigations ; 9163)

Bibliography: p. 23–24.

Supt. of Docs. no.: I 28.23: 9163.

1. Process control. 2. Radio telemetry. I. Isaacson, A. E. (Alan E.) II. Maysilles, J. H. (James H.) III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 9163.

TN23.U43 [TS156.8] 622 s [669] 87-600436

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	ms	millisecond
dB	decibel	mV	millivolt
ft	foot	mV/s	millivolt per second
Hz	hertz	pct	percent
in	inch	rpm	revolution per minute
lb	pound (mass)	V	volt
μs	microsecond	V ac	volt, alternating current
μA	microampere	V dc	volt, direct current
min	minute	yr	year

MEASUREMENT AND CONTROL IN INDUSTRIAL PROCESSES USING AN ANALOG-TO-DIGITAL TELEMETRY SYSTEM

By P. J. McDonough,[1] A. E. Isaacson,[1] and J. H. Maysilles[2]

ABSTRACT

The Bureau of Mines designed and tested a hardware-software system for measuring on-line corrosion rates of materials in a rod mill in operation. Currents ranging from 10^{-6} to 10^{-3} A and potentials in 1-mV increments were converted to a digital signal. The digitized data were frequency-modulated and transmitted from a rotating ball mill to an FM receiver, where they were decoded by computer and then processed in real time using assembly language software. This design approach would allow accurate measurement and control of systems where signals of small amplitude and large ranges are present.

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INTRODUCTION

Economies are continually being sought in industrial operations through the use of effective process monitoring and controlling techniques (1-5).[3] The mining industry is no exception. Ore mining and milling operations that must be made cost-effective include vehicle loading, material conveying, ore grinding, and flotation reagent addition. Power consumption and equipment lifetime are major considerations. In each case, accurate measurement of process phenomena is critical, and this task is the most difficult from the system design point of view.

All physical measurements are made through use of a transducer (6-7). Often the transducer converts the variable to be determined into an electrical signal, which must be transmitted to an interpreting operator or hardware system. The electrical signal may be a very small potential or current that is susceptible to distortion by noise, which may be caused by electromagnetic radiation, mechanical vibration, or changes in temperature or pressure. Accurate transmission and interpretation of the transduced signal is therefore a critical element in proecss control.

The first step in the transmission process is often amplification, which is followed by a transfer of the signal to the interpreting equipment. The two transfer methods commonly used are direct cable connection and radio transmission. Cable connection is often preferable if the distance is relatively small and the transducer is stationary. As distance increases, the cost of the cable becomes significant. Also, if analog data are being transmitted at a high frequency, or digital data at a high baud rate, the impedance of the cable must be matched with that of the transmitting and receiving equipment, or the signal may be lost or distorted through reflection. Radio transmission is therefore preferable if the distance involved is great or if the transducer is mounted on a moving piece of equipment.

In the past 25 yr, major advancements have been made in four areas of process control: development of microprocessing systems, inexpensive manufacturing of high-speed electronics devices and integrated circuits, development of new sensing devices, and a better understanding of the mathematics of signal processing (8-10). Also, the price of radio systems and hardware used to encode and decode data has dropped dramatically over the last 10 yr. These two phenomena have made the development of economical and effective control systems a much more achievable goal.

To investigate the potential for using digital data processing and radio transmission techniques in process monitoring and control systems, the Bureau of Mines designed and field tested a system for making corrosion rate measurements on ferrous alloy specimens inside an operating commercial rod mill, as part of a program to determine the relative importance of corrosion and physical attrition in the wear of mill liners and grinding rods and balls. Measurements made using the Bureau-designed electronics system were compared with those obtained using a direct wired system and commercially available electronics equipment.

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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

DESIGN OF INSTRUMENTATION FOR CORROSION STUDIES

ELECTROCHEMISTRY OF CORROSION (11-13)

When a metal is in contact with an electrolyte, a liquid through which current can be transported by the movement of ions, electrochemical reactions can occur at the metal-electrolyte interface such as those represented by reactions 1, 2, and 3:

$$M \rightarrow M^{2+} + 2\ e^-$$

$$\text{(anodic reaction)}, \qquad (1)$$

$$H_2O + 1/2\ O_2 + 2\ e^- \rightarrow 2\ OH^-$$

$$\text{(cathodic reaction)}, \qquad (2)$$

$$2\ H^+ + 2\ e^- \rightarrow H_2$$

$$\text{(cathodic reaction)}. \qquad (3)$$

In steady state, the number of electrons generated by the anodic reaction must equal the number consumed by the cathodic reactions. Since the reactions are coupled, the anodic current across the interface, I_a, and the cathodic current, I_c are equal in magnitude:

$$/I_a/ = /I_c/ = I_{ex}. \qquad (4)$$

The potential at which this condition exists may be called the open circuit, corrosion, or rest potential. The magnitude of the dynamic current, I_{ex}, is called the exchange current. In order to determine the rate of metal corrosion by reaction 1, this current must be determined. This task presents a problem from the instrumentation standpoint because instruments can only measure a net current, which is zero at steady state. Therefore the exchange current must be determined indirectly by applying potentials above and below the rest potential, measuring the resulting currents, and interpolating the results.

When a nonzero current exists, the electrons that flow in or out of the metal must be transferred via a source or sink. A separate electrode connected to the metal specimen by a wire can serve as the transfer medium if the surface characteristics of the electrode material allow electron flow across the electrode-electrolyte interface easily; in other words the electrode material must allow a relatively large exchange current. One material that meets this requirement is graphite, which was the electrode material used for the experiments described in this report.

FUNDAMENTALS OF POTENTIOSTAT DESIGN (14-15)

A device that applies a sequence of carefully controlled potentials and measures the resulting currents in an electrochemical cell is called a potentiostat. Application of a potential that changes linearly with time is called a linear polarization scan. Figure 1 shows idealized results of such a scan. The exchange current is determined by analyzing a plot of potential versus the logarithm of the absolute value of the current.

Figure 2 shows the essential components of a potentiostat. The device consists of a potential source, an operational amplifier, and a current measuring circuit. The fourth component of the experimental system is an electrochemical cell that contains three electrodes: a working

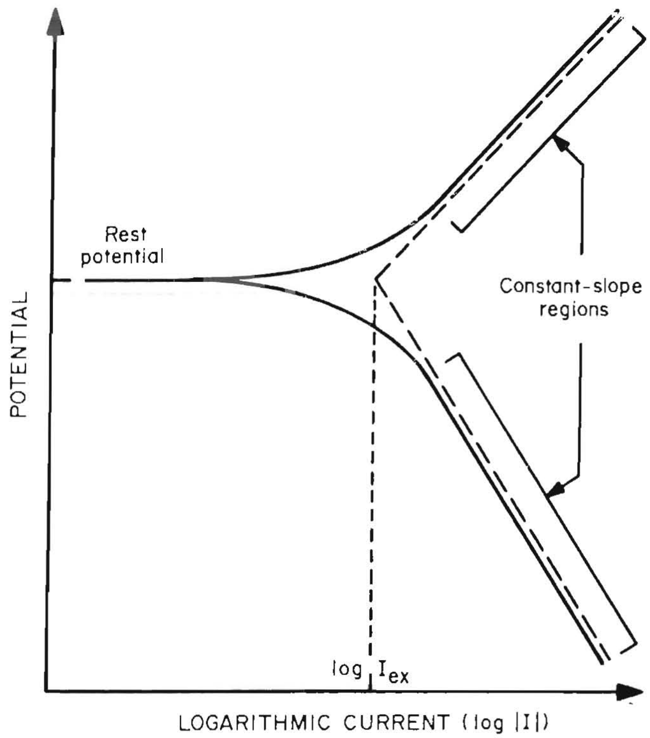


FIGURE 1.—Potential-current data used to determine corrosion rate.

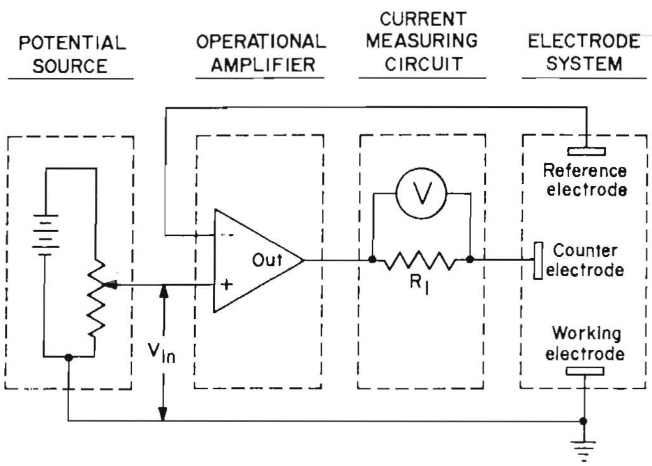


FIGURE 2.—Potentiostat components.

electrode, which is a specimen of the metal being examined, a counter electrode, which is the electron source or sink, and a reference electrode, which serves as a standard reference point for determining potential values. The reference electrode used in these studies was the saturated calomel electrode.

The potential between the working and reference electrodes is applied by using an operational amplifier, or op amp.[4]

The way in which this device functions may be understood by considering two rules:

1. The potentials at the plus (+) and minus (-) inputs must be equal.

2. A current is supplied at the output (Out) to achieve this equality.

Refering to figure 2, if rule 1 applies, then the difference between the working electrode and the reference electrode potentials is equal to V_{In}:

$$V_{In} = V_{WE} + V_{RE}. \qquad (5)$$

The impedance of the op amp at the minus input is sufficiently high that negligible current flows through the reference electrode; V_{RE} must therefore be constant, since no current-impedance (I-R) drop occurs in that part of the circuit. When V_{In} changes, V_{WE} must change, since V_{RE} is fixed. A potential drop, V_{WE_S}, occurs at the electrode surface when current flows between the electrode and the electrolyte, and this drop is equal to the current times the interfacial, or surface, resistance, R_S:

$$V_{WE_S} = I \cdot R_S. \qquad (6)$$

The working electrode potential, V_{WE}, can therefore be adjusted by changing the current through the electrode.

Current Measuring Circuit

Corrosion rate experiments made in the laboratory using a commercial potentiostat showed that currents for wrought steel would be in the range of 10^{-6} to 10^{-3} A (25-27). The current range for high-Cr steel would be 10^{-9} to 10^{-6} A. The combined range then needed for the amplifier would be 6 orders of magnitude. Since the steel specimens were run separately, it was decided to design an amplifier that would cover 3.5 orders of magnitude.

[4]Descriptions of the devices and techniques discussed in the remainder of this report can be found in references 16-24.

When the wrought steel specimens were being tested, a 10-ohm resistor was used for R_1 (fig. 2). When high-Cr steels were being tested, a 10,000-ohm resistor was used for R_1. Resistor R_1 was physically set into the circuit and not changed during the experiment.

Once the initial range was set by choosing a value of R_1, the gain of the current amplifier was operated in an autoranging mode, which was accomplished by electronically switching in and out the required feedback resistors.

In order to measure currents as low as 10^{-9} A, the first stage of the current amplifier (fig. 3) was designed to have an input bias current, I_b, which is the current that flows in or out of the measuring circuit, that is much lower than the current being measured, I_p. The primary amplifier has an input bias current of 10^{-12} A, resulting in a measurement error on the order of 0.1 pct (28). This amplifier was built from discrete components, since commercial integrated instrumentation amplifiers requiring this small an input bias current were not available.

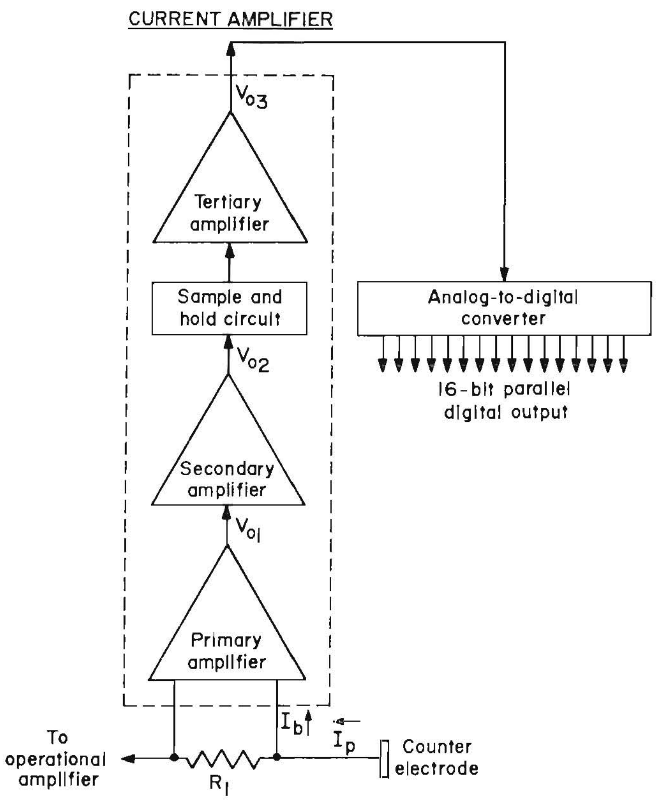


FIGURE 3.—Current measuring circuit in potentiostat.

The primary amplifier was also designed to reject noise. The common mode rejection ratio (CMRR), which is a measure of ability to reject signals such as resistor noise that appear at both ends of the resistor and thus both input terminals of the amplifier, is 110 dB. The gain of the noise is thus one-third of a millionth that of the signal.

The output of the primary amplifier, V_{o1}, is amplified by the secondary amplifier. The output voltage of the primary amplifier is large enough that input bias into the secondary amplifier creates a negligible I-R drop; therefore a commercially available instrumentation integrated circuit was used for the secondary amplifier. Its output signal, V_{o2}, is sufficiently high in magnitude to be processed by the sample and hold circuit, which acts to reduce random noise by integrating the signal over a period of time. Every 190 ms the signal stored by the sample and hold circuit is read and amplified by the tertiary amplifier, which boosts that signal to approximately 5 V to increase the accuracy of analog to digital conversion. In order to produce a signal of approximately 5 V for use by the analog-to-digital converter, the gain of the three-amplifier combination must be adjusted to produce a signal of this magnitude for each current measurement, and the amount of gain used must be known. Gain is controlled by electronically changing resistors, as illustrated in figure 4. Twelve gain values, each different by a factor of approximately 2, are possible. Every 190 ms a 3-µs pulse from the reset clock sets the counter to zero. At the same time, switch S_1 is closed, switches S_2 and S_3 are opened, and all switches in the gain control section except S_a are opened. The resulting gain factor is 2^{12}. The output of the current amplifier is sent to a comparator, which compares the value to a reference value, V_L, of 5 V. If the input value is greater than V_L, no action is taken, and the next pulse from the counting clock advances the counter setting, which closes switch S_b, setting the gain factor to 2^{11}. Thus, the counting clock

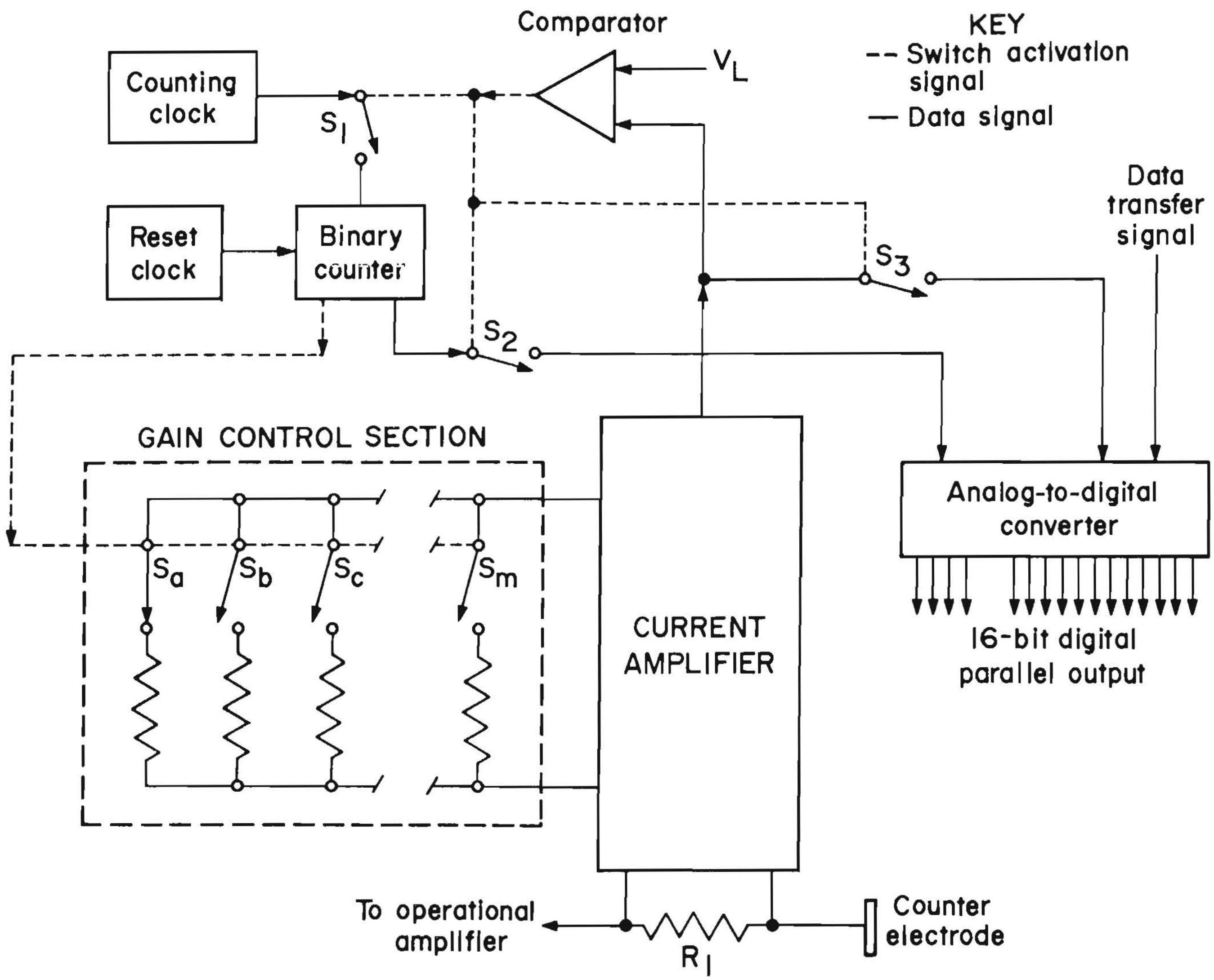


FIGURE 4.—Automatic gain control for current measuring circuit.

sends a signal to the counter every 3.3 ms until the resulting signal from the current amplifier is less than 5 V, at which point the comparator opens switch S_1, which stops the action of the counting clock, leaving the counter setting at its current value and the switches in the gain control section as set. The comparator also closes switches S_2 and S_3, and the counter setting and amplifier output are sent to the analog-to-digital converter. The converter receives a read, or data transfer, signal 80 ms after the reset clock pulse, which is enough time for the entire range of gain adjustment to be accessed; at this time the current amplifier and binary counter outputs are converted to digital form. The final 16-digit signal from the converter that represents the measured current value consists of 12 bits that correspond to the current amplifier output and 4 bits that correspond to the gain factor.

Applied Potential Control Circuit

In the discussion of potentiostat design, the applied potential source was shown in figure 2 as a combination of a battery and a variable resistor. In practice, the potential value is controlled electronically and changed in increments with time, as shown in figure 5. This type of potential versus time response is generated by the circuit shown in figure 6. A pulse from a crystal-controlled clock is fed every 190 ms to a binary counter, which converts the number of clock cycles into a 12-bit binary number. This number is then converted to a current that is proportional to the number by a digital-to-analog converter. The output of this converter, I_o, cannot be used directly as a potential source, so it is amplified to a potential, V_{in}, which is the applied potential shown in figure 2.

INSTRUMENTATION OF A COMMERCIAL ORE GRINDING MILL

An instrumentation system was designed to measure corrosion rates of a metal specimen inside an operating rod mill. The entire system is diagrammed in figure 7; sections that were mounted on the mill are shown in figures 8 and 9. The main section of the mill-mounted equipment, which includes the potentiostat system, operating interface, radio transmitter, and a battery pack, is 3-1/2 ft long. The total weight of the equipment is approximately 60 lb.

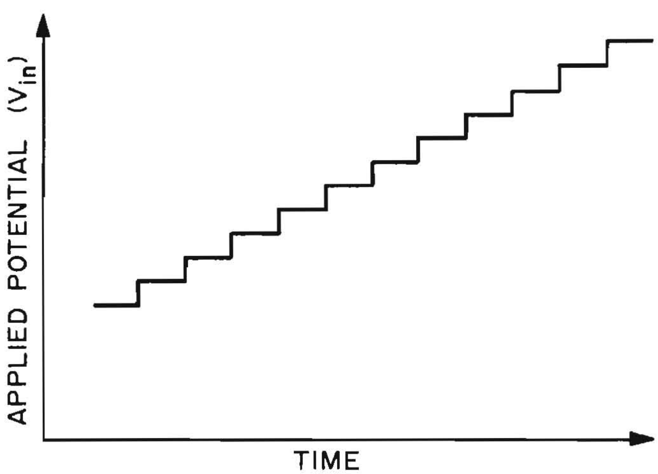


FIGURE 5.—Potential applied in linear polarization scan.

The mill used for the study was 9 ft in diameter by 14 ft long, half-filled with steel rods from 1/2 to 2 in. in diameter, and rotated at 18.4 rpm. The rotation of the mill lifts the rods up one side and then they fall against the mill wall and each other with a tumbling action. Ore is fed into the mill as a slurry with water in particles up to 1/2 in. in size. The ore particles are crushed as they are caught between the impacting bodies.

The electrode system used consisted of working, counter, and reference electrodes mounted inside a hollowed-out bolt that was used to attach sections of lining material inside the mill to prevent wear of the mill shell. A diagram of the electrode assembly is shown in figure 10; a more complete description is given in reference 26.

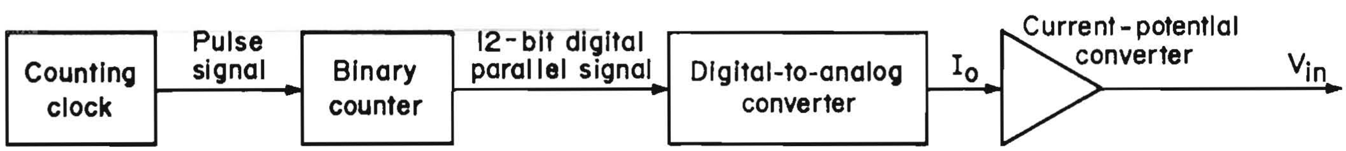


FIGURE 6.—Technique for generating applied potential in potentiostat operation.

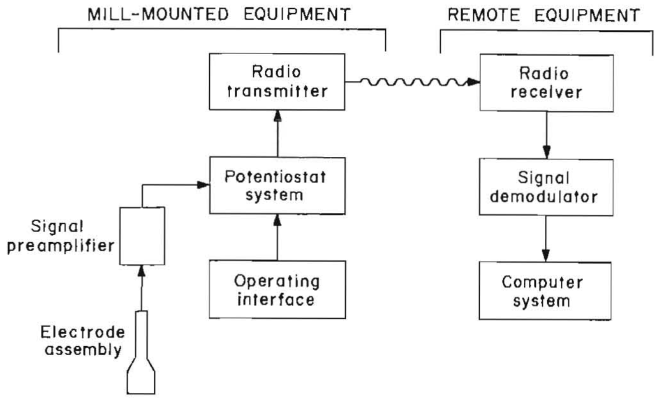


FIGURE 7.—Components of corrosion rate measurement system.

Making corrosion rate measurements in this environment presents the following four types of instrumentation design problems:

1. Electromagnetically and mechanically induced electrical noise is superimposed on the electronic signals being processed.

2. Equipment must be calibrated and its operation controlled while it is mounted on a rotating device.

3. Data generated by the mounted equipment must be transferred to a storage system.

4. All equipment must be portable to some degree.

The following sections explain how these problems were overcome.

SUPPRESSION OF ELECTROMAGNETICALLY INDUCED NOISE (6, 29)

Electromagnetic noise comes primarily from the large electric motors used to turn the mill. The electric motors are less than 10 ft from the mill and are inadequately shielded. Noise is generated in integral multiples of 60 Hz and superimposed on the test signal leads. To minimize the magnitude of this type of noise, the leads are shielded and the signal is boosted by a preamplifier mounted close to the electrode assembly.

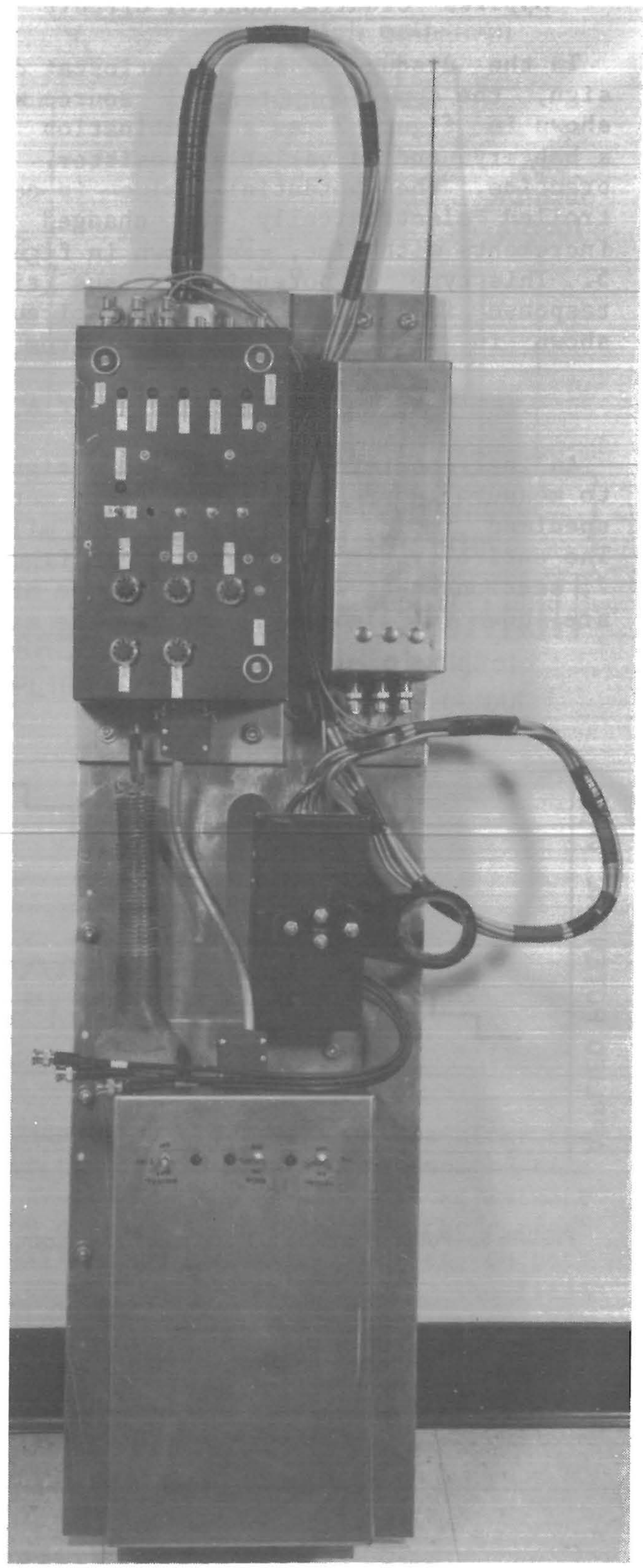


FIGURE 8.—Potentiostat and associated mill-mounted equipment.

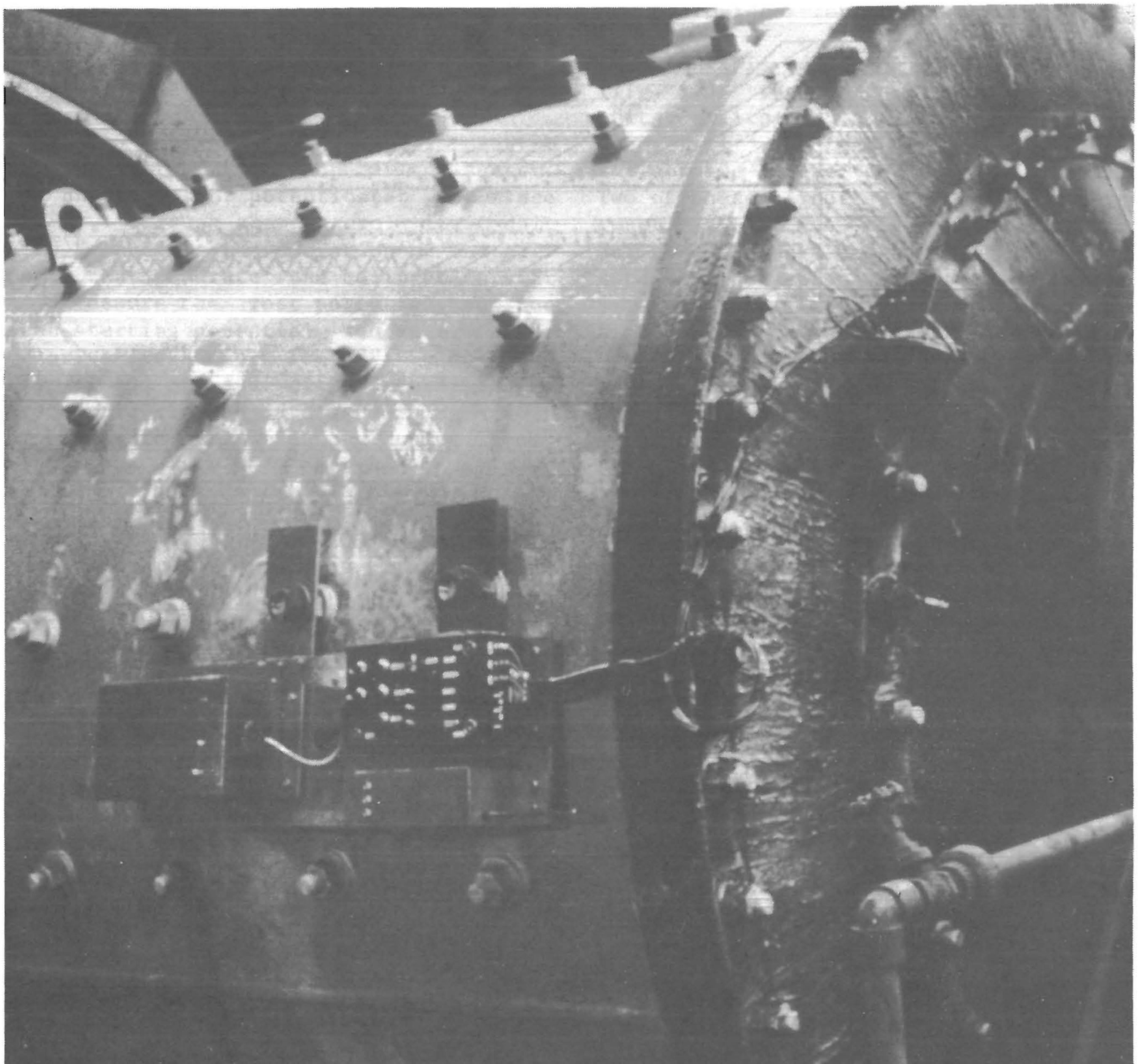
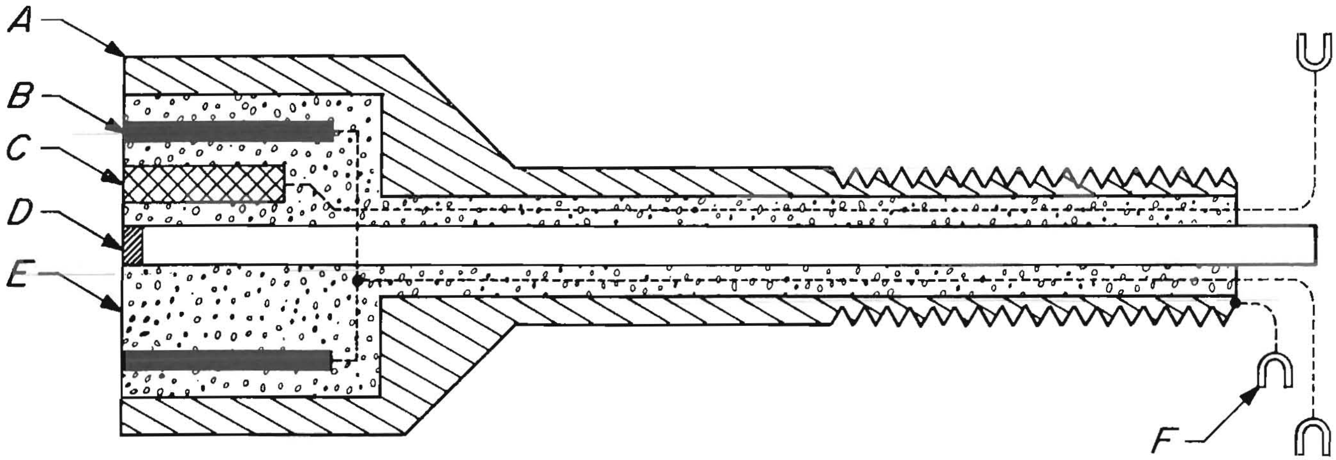


FIGURE 9.—Field installation of equipment.



KEY

A Hollowed liner bolt

B Graphite counter electrode

C Metal specimen working electrode

D Tube containing conducting gel salt bridge

E Epoxy filler

F Ground connection

FIGURE 10.—Electrode assembly diagram.

The first stage of the preamplifier is a low-pass filter that attenuates signals of 10 Hz or higher. The remaining test signal is then amplified to a potential of 2.5–5.0 V and transmitted to the potentiostat. The output of the preamplifier is several orders of magnitude greater than the electromagnetic noise.

ELIMINATION OF MECHANICALLY INDUCED ELECTRICAL NOISE

Additional electrical noise is generated by the reference electrode being vibrated. Some vibrations are caused by rods striking the sides of the mill, others originate in the motor and bearings. A significant part of the noise is generated in frequencies that are integral multiples of the mill rotational speed of 0.31 Hz. These frequencies are not filtered out by the preamplifier. The noise can, however, be removed by processing the data through a fast Fourier transform (FFT) numerical filter when it is computer processed (9, 30).

CONTROL OF POTENTIOSTAT OPERATION

In order to run a polarization scan in a laboratory test or on a rotating mill, the operator or the system hardware must perform the following actions:

1. Calibrate the equipment.

2. Measure the rest potential.

3. Determine and set the potential at which the scan is begun.

4. Run the polarization scan and record the data.

5. Terminate the scan and turn off the equipment.

With laboratory equipment, all operations are performed by the operator, who sets switches and makes adjustments at the correct times. Mechanical switches and knobs cannot be set, however, on a rotating mill. A system was therefore designed in which adjustments could be made using light-activated devices.

Optically Activated Switching System

Figure 11 is a functional diagram of the potentiostat operating system. The photoresistor-potentiostat interface (PRPI), through the control logic unit (CLU), controls the operation of the circuits that generate the calibration signal, measure the rest potential, set the scan starting potential, and generate the polarization scan. The PRPI also turns the system on and off. Information is transferred to the data processing system by FM radio transmission, using techniques that will be described in a later section of this report.

Photoresistor-Potentiostat Interface

The PRPI is composed of three sections (fig. 12): the photoresistor (PR) circuits, a flip-flop circuit, and a binary counter (17) Three PR's are mounted on the outside of the potentiostat chassis. Two of these circuits, the set PR and the reset PR, are used to send a pulse signal to the binary counter, which in turn sends a binary signal of value 0 through 4 to the CLU. Table 1 lists the functions performed by the CLU according to the signal received. The binary counter setting is advanced by the operator shining a beam of light alternately on the set and reset PR's. Light of sufficient intensity causes the PR's to close their accompanying switches. Momentarily

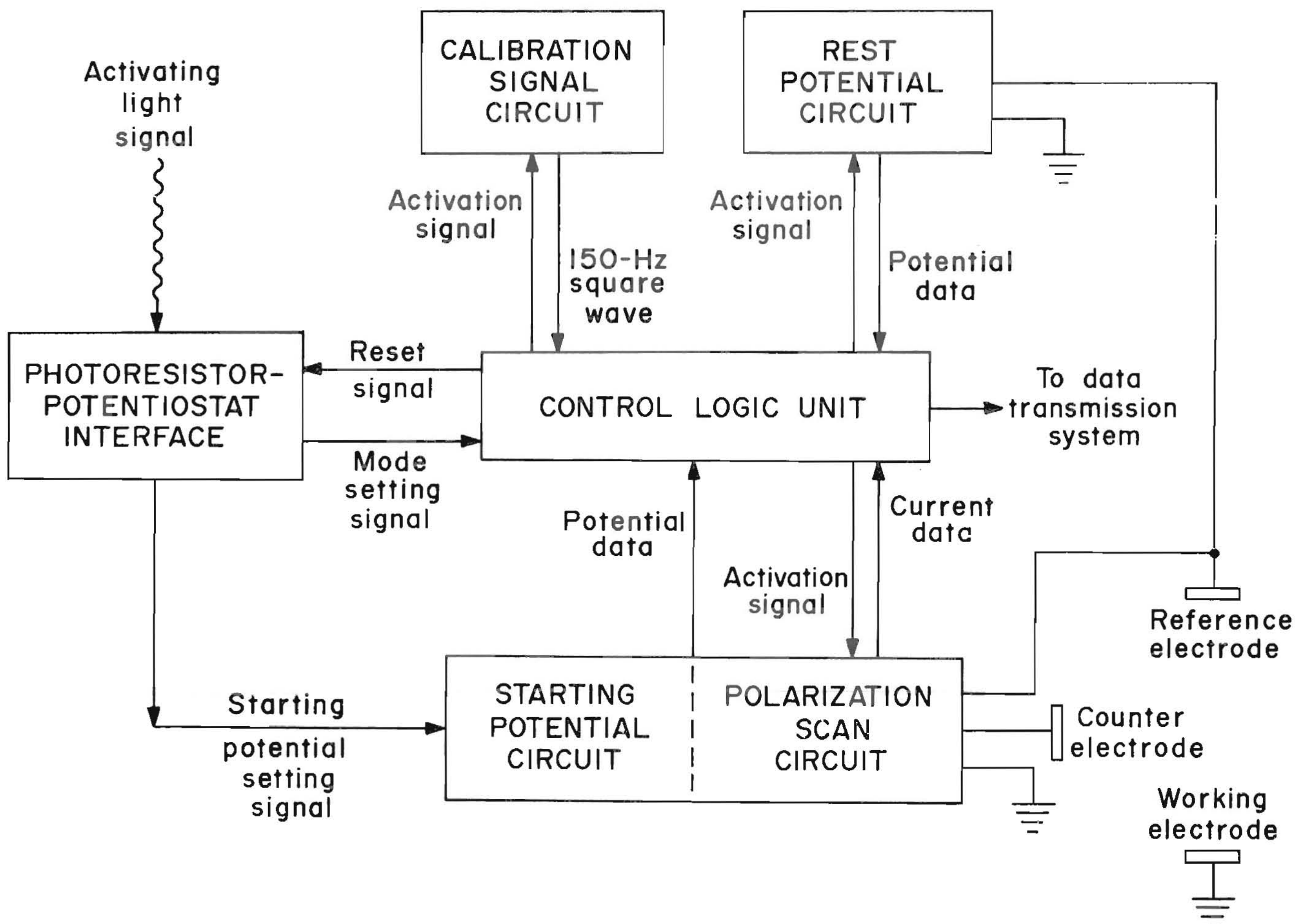


FIGURE 11.—Potentiostat operating system.

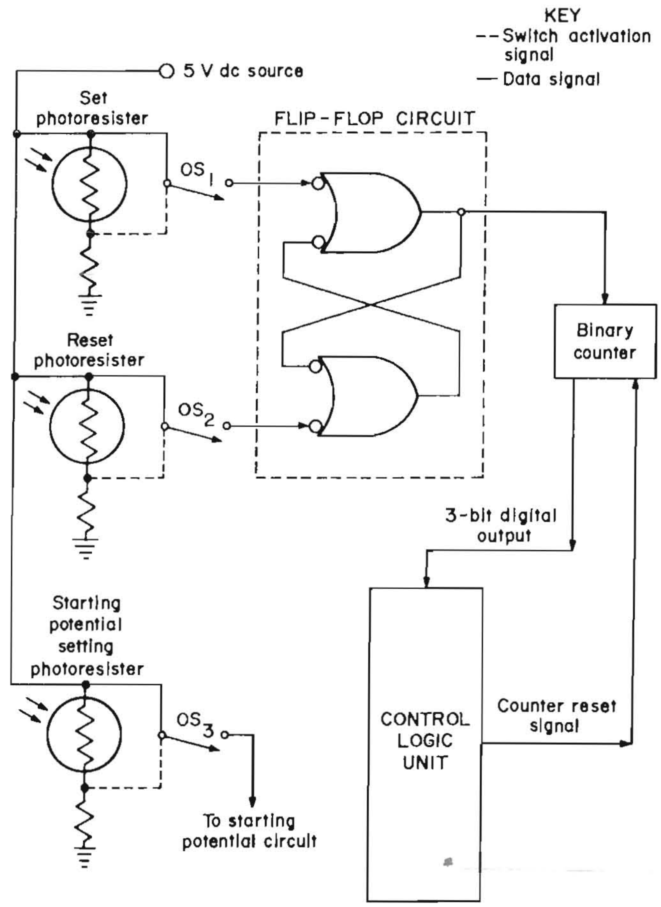


FIGURE 12.—Photoresister-potentiostat interface.

closing switch OS_1 causes a pulse signal to be sent through the flip-flop circuit to the counter, advancing the setting by one. The flip-flop circuit is also set by this process so that another signal cannot be sent by closing OS_1; the circuit must be reset by momentarily closing switch OS_2 using the reset PR. This design is intended to prevent the counter from being advanced randomly by lighting phenomena extraneous to the system. The two PR's are mounted on opposite corners of the chassis so that they can be activated independently by the operator.

The third PR is used to control the starting potential setting circuit. This operation will be explained in a later section.

Calibration Signal Circuit

This circuit generates a square wave of 150 Hz. The low and high values of this signal are interpreted by the frequency shift keying (FSK) (31) circuit to be logic values of zero and one, respectively. These values are each converted by the FSK to a different frequency, and these frequencies are alternatively transmitted by the FM radio. The receiver that is connected to the data processing system is then tuned for proper reception of the two frequencies.

Rest Potential Circuit

Activation of the rest potential measuring circuit connects the reference and working electrodes to a digital potentiometer, as shown in figure 13, by closing switch S_4. Operation of the potentiometer is similar to that of the automatic gain control for the current measuring circuit of the potentiostat.

TABLE 1. - Operation of potentiostat control logic unit by photoresistor-potentiostat interface

Binary counter signal value	Control logic unit function
0	Activates calibration signal generation circuit.
1	Activates rest potential measuring circuit.
2	Activates starting potential setting circuit.
3	Activates polarization scan circuit.
4	Places all four circuits on nonactive status.

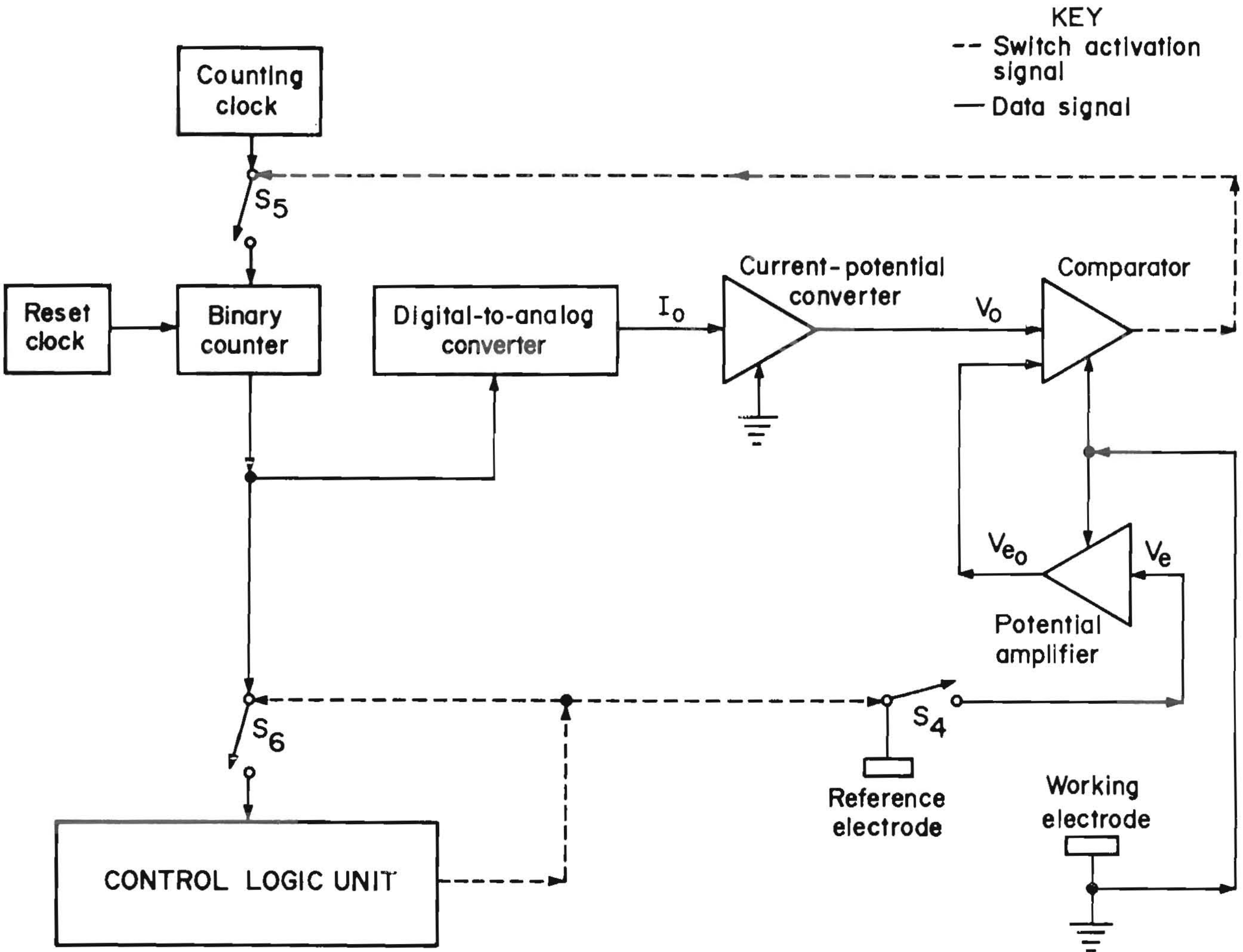


FIGURE 13.—Rest potential circuit.

The sequence of actions is shown in figure 14. Every 190 ms the reset clock sends a 3-μs pulse that sets the binary counter to zero. The counter is advanced every 1.1 μs by the counting clock. The counter setting is continually converted by the digital-to-analog circuit to a current proportional in value, which is then transformed to a potential, V_o, by the current-potential converter. This value is then compared with a value, V_{e_o}, that corresponds to the potential difference between the reference and working electrodes. As soon as V_o becomes larger then V_{e_o}, the comparator stops the action of the counting clock by opening switch S_5. The counter setting then remains constant until the next data transmission cycle is started by the reset clock. The counter setting is passed to the CLU for transmission to the data processing system through switch S_6, which is closed when the rest potential circuit is active.

The potential difference between the electrodes, V_e, was on the order of 0.5 V for the particular measurements being made in this study. This value was amplified by a factor of 10 so greater accuracy could be obtained when voltages were compared at the comparator. The potential difference was therefore boosted

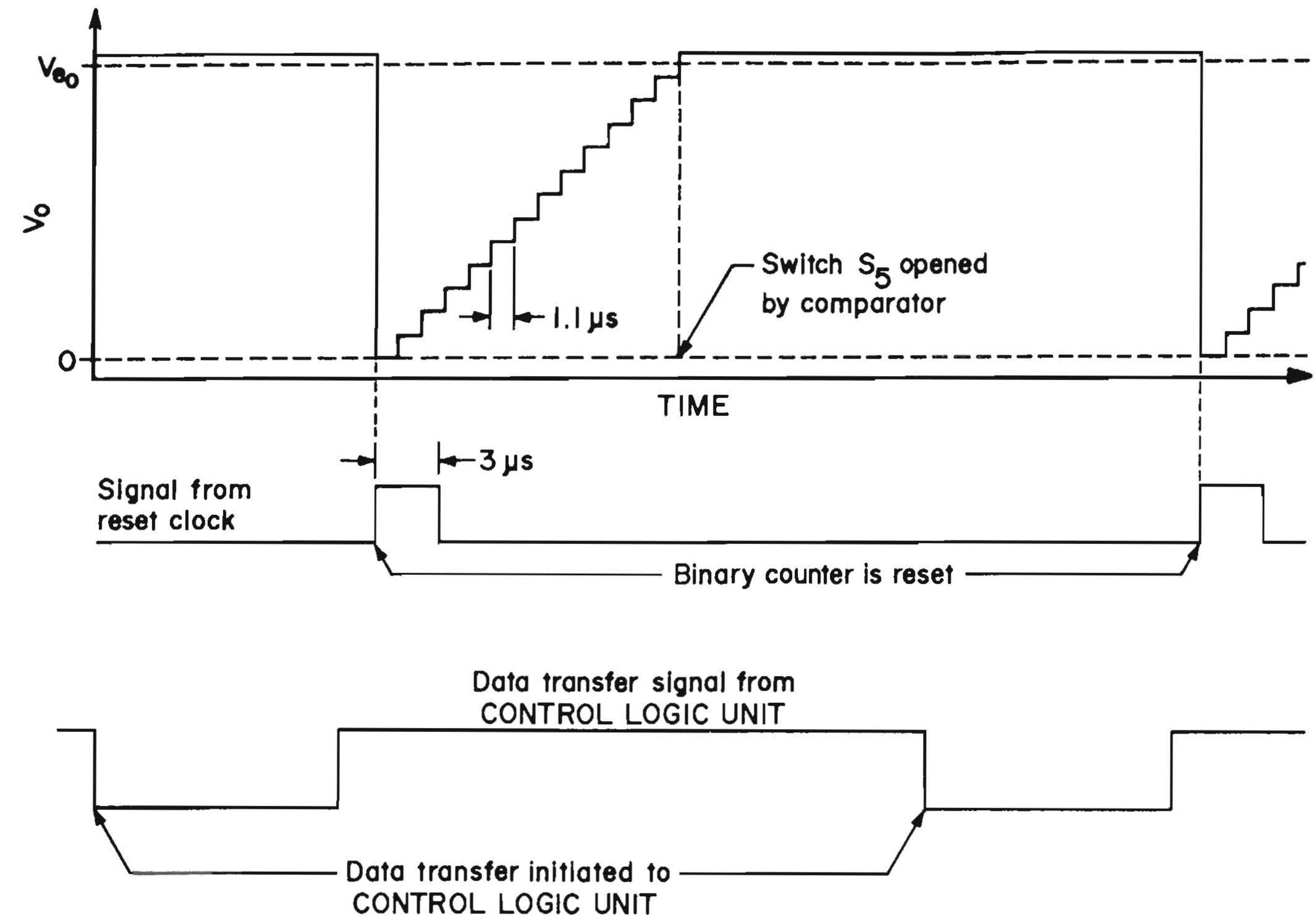


FIGURE 14.—Timing sequence used by rest potential circuit.

by a potential amplifier. For the experiments described in this report, the amplifier gain was internally set to be 10. Internal gain setting eliminated the need for external resistors, which minimized temperature drift of the setting, and maintained a large common mode rejection ratio for signal processing. The internal impedance of the amplifier was large enough to minimize errors generated by the bias current requirement for operation.

Starting Potential and Polarization Scan Circuitry

The circuitry used for setting the scan starting potential and performing the linear polarization scan is illustrated in figure 15. The potential values used in both actions are determined by the setting of the binary counter. To set the scan starting potential, the counter is advanced by shining a beam of high-intensity light on the starting potential photoresistor (fig. 12), which closes switch S_7 and keeps it closed as long as the PR is activated by the light beam. The setting clock then advances the counter. The counter setting is transferred every 190 ms to the CLU and transmitted to the data processing system, where the corresponding potential value can be read by the operator on a cathode ray tube (CRT) screen. The setting clock operates at 75 Hz, and the entire range of the binary counter can be scanned in less than 1 min. When the counter setting reaches the top of its range, the next pulse from the setting clock resets the counter to the bottom of its range, and the scan sequence begins again. When the desired

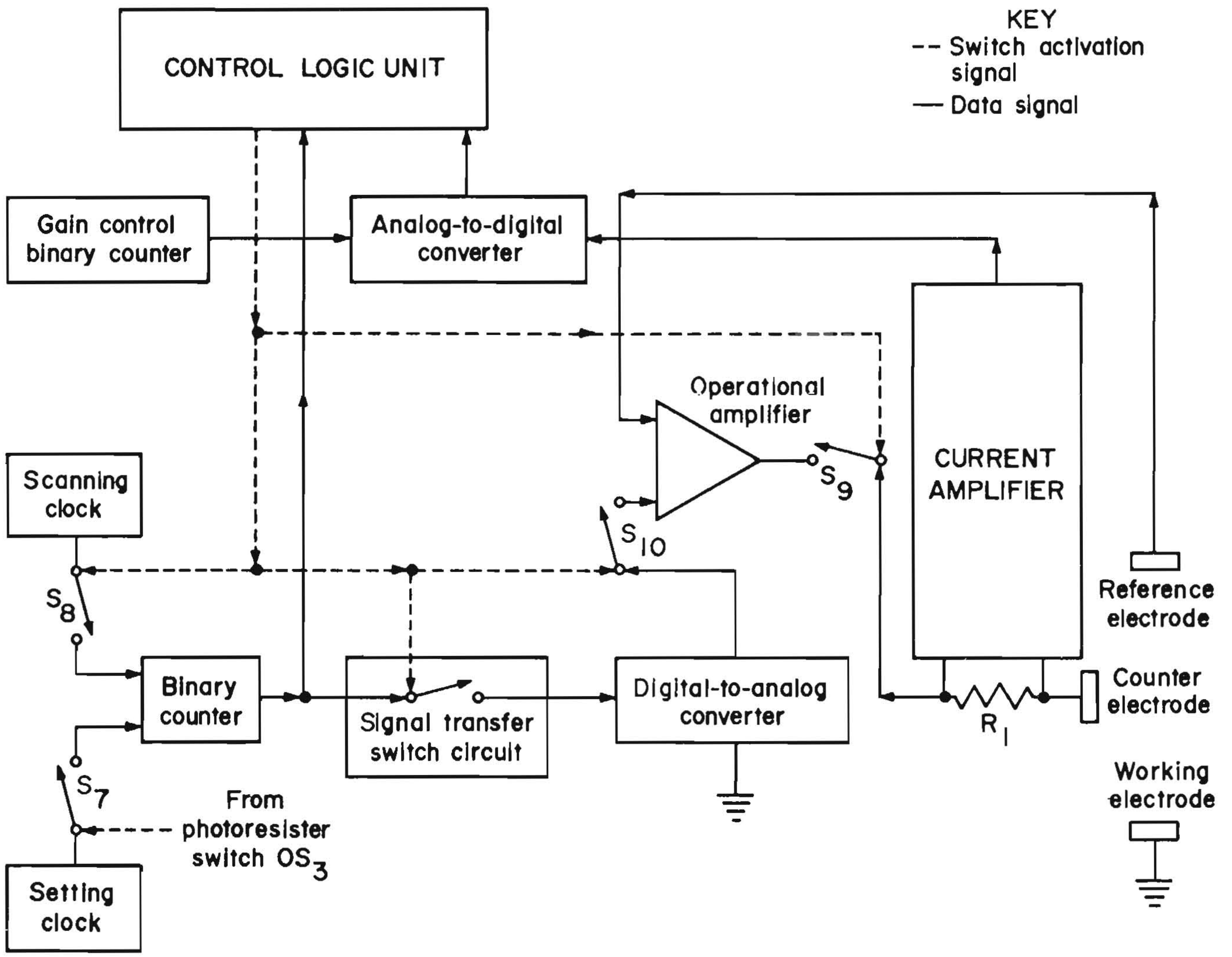


FIGURE 15.—Starting potential and polarization scan circuitry.

starting potential is set, the potentiostat system is optically switched from the setting mode to the scanning mode by the operator.

When the polarization scan is made, the binary counter setting is advanced by the scanning clock, which operates at 5.26 Hz. The corresponding potential value is increased at approximately 0.2 mV/s; a scan over a range of 200 mV therefore takes about 17 min. Operation of the scanning clock is controlled by the CLU, which closes switch S_8. The CLU also connects the electrodes to the scanning circuit by closing switches S_9 and S_{10}. The potential between the reference and working electrodes is applied by transferring the binary counter reading to the digital-to-analog converter through the signal transfer switching circuit. The switching circuit contains 12 electronic switches, one for each bit, that operate in concert. All 12 switches are closed when the potentiostat system is in the scanning mode. The digital-to-analog output is an analog current that is directly proportional to the digital input. As the scan proceeds, the digital signals representing the applied potential and the resulting current are transferred to the CLU. The data pair is transmitted every 190 ms to the data processing system.

DATA TRANSMISSION SYSTEM

Parallel to Serial Conversion

The system for transferring data from the CLU of the potentiostat to the data processing system is shown in figure 16. Twenty-eight bits of data must be transferred every 190 ms. If radio transmission over a single carrier frequency is used for the transfer, each data bit must be converted to one of a pair of frequencies, one frequency for logic zero and one for logic one. Simultaneous transmission of 28 bits would therefore require the use of 56 discrete frequencies, and the required data coding and decoding equipment would be complex and expensive. An alternative method was used in which the bits were transferred in sequence, which requires only two frequencies. The data, however, must first be converted from parallel to sequential, or serial, form. The first step in the conversion procedure is the assembly of data bits into eight bit words, which is illustrated in figure 17. Data are processed in sets of five words, which are assembled at a set of five interfaces. The first word is a programmed marker, which is always the same, that denotes the beginning of the data set. The data processing system is programmed to identify the marker, interpret the next two words as the current value, and interpret the following two words as the potential value.

The current value consists of 12 magnitude bits and 4 gain bits, which are assembled into two words. The current value is transmitted with the two most significant gain bits and the six most significant magnitude bits in the first word, the two least significant gain bits and the six least significant magnitude bits in the second word. The potential value is transferred as the final two words of the data set. The potential value consists of only 12 data bits, leaving available 4 bits for additional

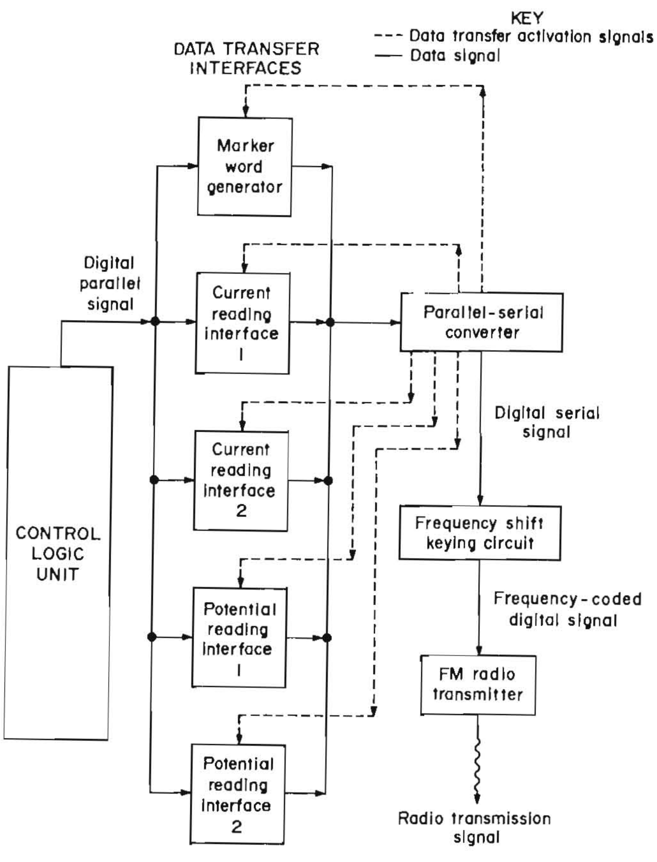


FIGURE 16.—Data transmission system.

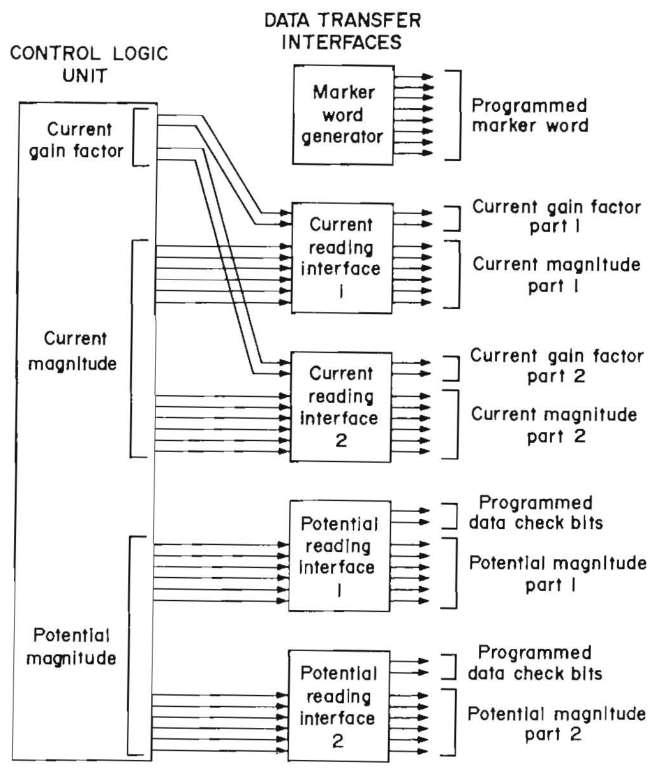


FIGURE 17.—Assembly of data words to be processed.

information. The first two bits of each potential value words are programmed, as is the marker word, to be constant. The first potential word contains two marker bits and the six most significant bits of the potential value; the second word contains two marker bits and the six least significant potential value bits. When data are transmitted, the processing system checks the marker bits to see if the correct transmitted values are being received.

All five words are arranged in the same two-bit, six-bit format to simplify processing by machine language programming.

The five eight-bit words are read in sequence by a universal asynchronous receiver-transmitter (UART) unit, which converts the parallel signal to a sequence of signals (32-34). The UART output for the word 10101010 is illustrated in figure 18. The output is always one of two values, corresponding to data logic levels zero and one. When data words are not being processed, the output is constant at level one. When a word is processed, the UART first sends a start bit, which is logic zero, for 3.3 ms to indicate to the data processing system that a word is about to be transmitted. Next, the UART sends the eight data bits at the rate of one every 3.3 ms. The UART then sends a parity bit, the value of which is determined as follows: the number of level one bits in the word is added; if the number is even, the parity bit is set to zero, and if the number is odd, the parity bit is set to be one. The number of level one bits transmitted with each word is therefore always even. The data processing system adds the number of level one bits received in each word to see if errors have occurred in transmission or reception. The odds that two bits in a given word will be altered during the transmission-reception process are 1 in 10,000; the data transfer process is therefore 99.99 pct accurate (35).

After all 10 bits have been transmitted, the UART sends a constant logic level one signal, providing a positive indication that the word transmission is terminated.

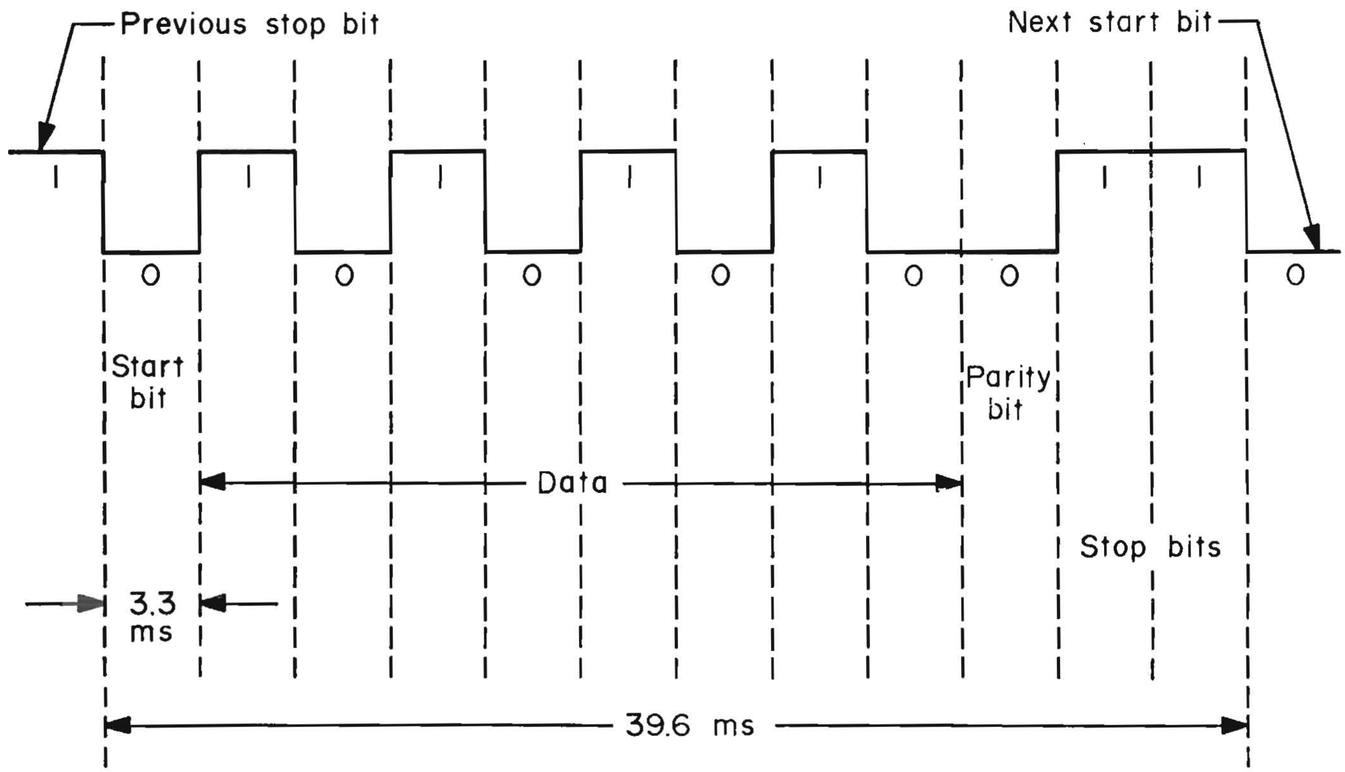


FIGURE 18.—Word structure of UART output.

Radio Transmission of Data

The constant-value logic level zero and one signals from the UART must each be converted to different frequencies for transmission to and decoding by the data processing system. Frequencies in the audible range were chosen so that a standard voice transmission system could be used. The UART output corresponding to logic levels zero and one was converted to frequencies of 960 and 1,250 Hz, respectively, by a device called a frequency shift keying (FSK) circuit, then passed to the microphone of a standard FM radio.[5]

[5]The Federal Communications Commission should be contacted regarding frequencies available for specific applications.

RADIO SIGNAL RECEPTION AND DATA CONVERSION

After the data have been coded and transmitted by the potentiostat-radio system, it must be received, decoded, and processed. Figure 19 shows the equipment used to perform these functions, except for the receiving antennas. The receiving radio used two antennas on opposite sides of the mill that were aligned parallel to the axis of the mill to insure that one antenna was always in line of sight of the transmitting antenna, in order to minimize signal amplitude modulation due to the rotation of the radio transmitter on the mill.

The FM receiver demodulates the radio signal to reproduce the frequency shift keyed signal, which now consists of

FIGURE 19.—Radio signal reception and data processing system.

960- and 1,250-Hz sine waves plus some 60-Hz noise. The signal is passively filtered to remove the noise, then transferred to the demodulator circuit, which produces a logic low output with a 960-Hz input, a logic high output with a 1,250-Hz input.

Serial to Parallel Conversion

The serial data consists of words with the format shown in figure 18: one start bit, eight data bits, one parity bit, and a stop signal. Each word must be converted into an eight-bit parallel format that the computer can accept. The conversion process is performed by a UART, the same type of device that is used in the parallel-serial conversion procedure by the data coding system. Both UART's operate in an asynchronous manner, which means that they are not controlled by the same timing device. The UART in the data receiving system must be able to determine a time interval within 1 pct of the interval used by the transmitting unit to avoid the possibility of misinterpreting the incoming signal (33). Crystal-controlled timing circuits were used in both systems to obtain the required accuracy.

The sequence and timing of the UART operation is shown in figure 20. At time t_0, the incoming signal drops from a logic high to a logic low value, indicating to the UART that a data word is about to be transmitted. The UART now performs actions in increments of 3.3 ms. After a one-increment delay, the input is examined for 3.3-ms periods, the first data bit being analyzed for the interval t_1 to t_2. At time t_2 the UART stores the logic value (in this case logic one) in its first register. From time t_2 to t_3 the input is analyzed and the result (logic zero) stored in register 2 at time t_3. This procedure continues until all eight registers have been assigned values.

From time t_9 to t_{10}, the UART reads the parity bit, then examines the eight registers, adds the number of logic values, determines what the parity bit should be, and compares this value with the value received. If the two values match, the

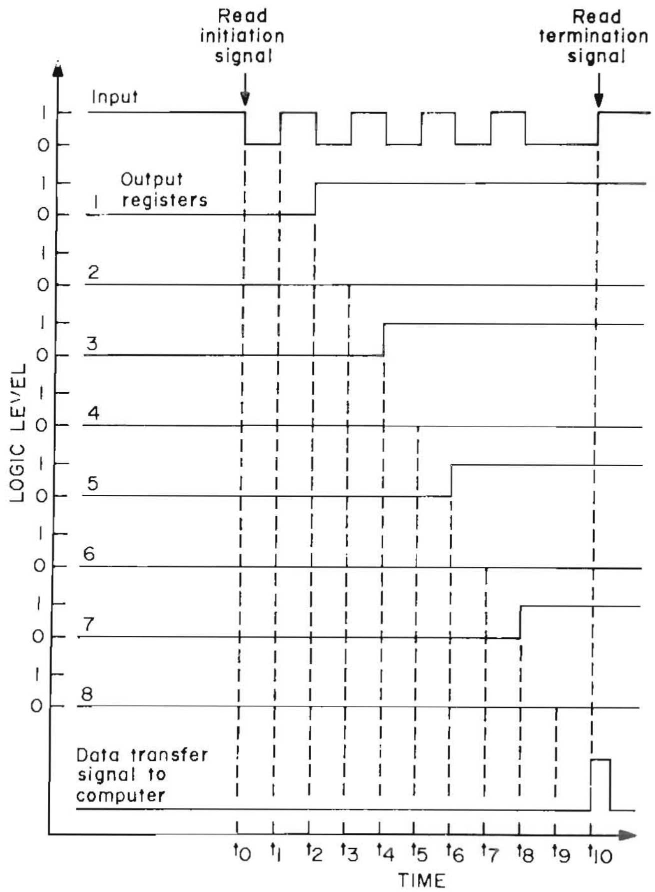


FIGURE 20.—Sequence of actions in serial to parallel data conversion.

UART sends a 5-V pulse signal to the computer indicating that a data word is ready for transfer.

Computer Data Processing and Storage

Data transfer from the UART to computer memory is controlled by use of a nonmaskable interrupt (NMI) procedure (36-38). The NMI consists of (1) a system that preempts control of the computer's central processing unit (CPU) and (2) a machine language program that performs the data storage function.

The radio receiver-demodulator system acts as an interface to the CPU in the same way as other peripheral units, as illustrated in figure 21. When the UART parity check is affirmative, the UART sends a logic low signal to the NMI input of the CPU. The CPU completes the current machine language instruction of the

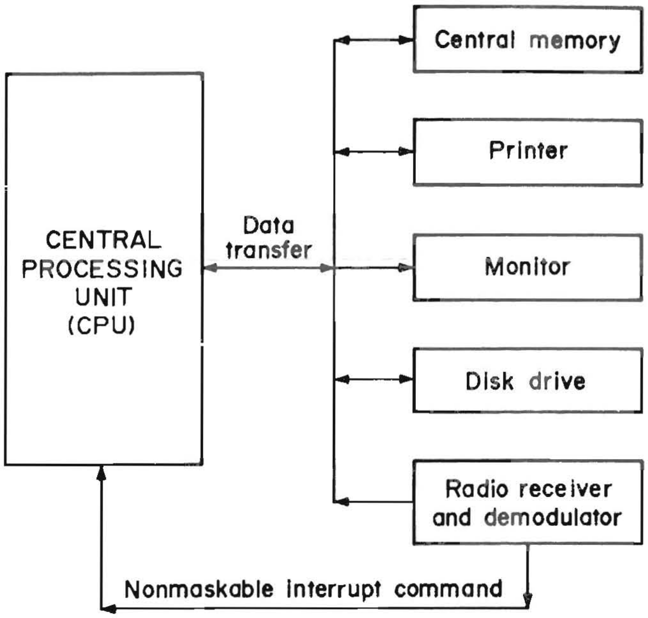


FIGURE 21.—CPU and peripheral devices.

program being run, then exists from that program by the following procedure. The CPU reads two locations of the read-only memory (ROM) that are reserved for the NMI vector. These locations each contain 8 bits of a 16-bit address, the value of which is set by the computer manufacturer. The CPU then accesses that address and interprets the contents of the address as the first intruction of the NMI service routine; this instruction is in fact a command to jump to a given address in the central memory, which is the first address containing the actual programmed service routine.

Since the CPU was interrupted while running a program, the stacks, accumulators, and registers contain information that applies to that program. This information must be saved so that the program can be resumed when the NMI has been completed. The first task of the service routine is therefore to store the contents of the CPU registers and stacks in central memory.

The CPU then reads a data pointer in central memory, which indicates the memory location where the last data word was stored. The pointer is updated by advancing its value one memory location.

The data transfer sequence, which is illustrated in figure 22, is then performed. Each peripheral device has assess to the word currently being processed by the CPU through a data bus, along which data can be transferred in either direction. An address, determined by the CPU, to or from which the word is to be transferred is also associated with the word, and the value of this address is accessed by the devices from the CPU along a separate bus, the address bus. The word is transferred only when two conditions exist simultaneously. First, the device involved in the transfer must be identified. The first four bits of address generated by the CPU identify the receiver-demodulator as being active in the transfer; the address decoder interprets the code and signals the device with a logic low pulse. Second, a separate signal must be sent by the CPU to indicate that transfer is actually to occur. When the device receives both signals at once, the input or output of that device is electronically connected to the data bus. The word is then transferred through the data bus from the receiver-demodulator to the memory location identified by the data pointer.

Following storage of the word, the NMI service routine reads the value of a counter to see if enough data have been stored to plot a point on the CRT screen. If so, a plot subroutine is called. This subroutine checks the last 20 memory locations where data have been stored, and if marker words are found in three consecutive correct locations (one every fifth word), the routine continues. The routine locates the two most recent potential value words, strips off the marker data bits, and recombines the data bits so that the first word contains the eight most significant bits, the second word the four least significant bits plus four bits set at zero. The routine then locates the words that correspond to the most recent current data stored. The four gain bits are stripped off and stored in a multiplier word that contains the four multiplier bits and four zeros. The twelve current magnitude bits are

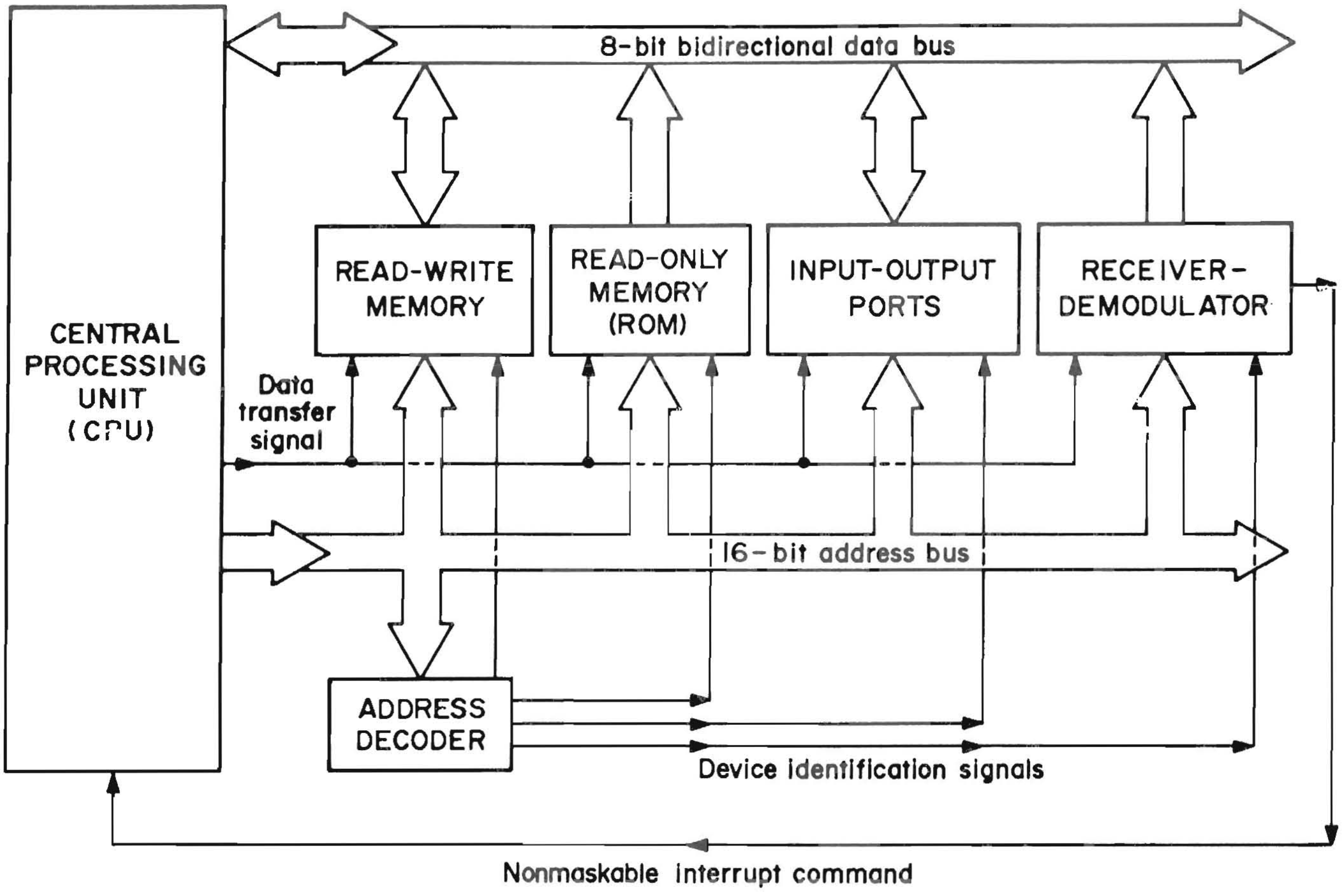


FIGURE 22.—Data transfer between CPU and peripheral devices.

stored in the same way as the potential value bits.

The potential and current values are then scaled for plotting to produce two eight-bit words. The scaled values are passed to a machine language subroutine that converts them to plot values and adds information needed by the CRT in order to activate the correct pixel cell. A discussion of this procedure is beyond the scope of this paper (38).

After the data have been interpreted and plotted, the NMI routine retrieves the interrupted program values for the stack, registers, and accumulator, and transfers them back to the CPU, returing the CPU to the state in which it was operating when the interrupt occurred. The CPU then continues to run that program. In practice, the interrupt procedure is completed so rapidly that the operator is unaware that it has occurred.

The program that is normally being run during this process is one that serves as a visual interface between the equipment and the operator. This program generates three types of output, the first of which is a display of the measured rest potential. Based on this value, the operator decides the potential at which the linear polarization scan is to begin. The operator then advances the program to the second visual output, which is the starting potential that is currently set. The starting potential circuit is then activated and the chosen value set by shining a light beam on the potentiostat-radio system as described previously; then the polarization scan is begun. The operator then advances the program to the third mode, which is a visual display of the results of the scan.

After the experiment is completed, the data are stored on floppy disk.

RESULTS OF FIELD TESTS

The first field test campaign using the telemetry system was made with the primary objectives of designing a portable system, determining if the system could operate in a commercial ore processing environment, and comparing the reliability of data resolution to that obtained using a direct wired analog signal system (26). The system previously tested consisted of the same type of electrode assembly and the same computer, but a commercial potentiostat and associated software were used and electrical connections were made through a set of copper contact rings mounted on the face of the mill. Shielded coaxial cables were used to connect the electrodes to the rings and connect the potentiostat to a set of spring-loaded carbon brushes, which maintained contact with the rings as the mill rotated.

The telemetry system was sufficiently portable that transportation, installation, and operation at a remote facility were performed without difficulty. The only external power required was a standard 110 V ac source for the computer system; the mill-mounted equipment was battery operated.

Operation of the potentiostat through the light-activated photoresistors was successful, but setting the polarization scan starting potential was slow because the photoresistor could only be activated for a fraction of a second per mill revolution.

One other major difficulty was identified during the field tests. Equipment using power that is derived from the same source that supplies heavy electrically powered equipment must be protected from extreme power surges. The computer used in these studies was damaged by a surge when one of the mills was turned on. Fortunately enough tests had been completed to satisfy the objectives of the campaign.

Six polarization scans were successfully made, three scans each on specimens of cast steel and wrought steel. Figure 23 shows a typical result for a scan made with wrought steel. Consecutive data points have been connected by horizontal lines to illustrate scatter. Resolution is generally within 50 pct, and the trend of the curve can be clearly identified. By comparison, figure 24 shows a typical result for the same material in a test made in a copper ore mill using the direct wired system. Variations of an order of magnitude are common; data averaging techniques are needed to analyze the scan.

Figure 25 shows the resolution possible in laboratory environments and illustrates the need for careful design of transducers and signal transfer techniques for use in industrial operations. This scan was made using the same equipment that was used to obtain the field test data shown in figure 24, except that the electrodes were mounted in a laboratory test cell, and the contact ring was not used (noise from the moving contacts had been shown to be insignificant). The telemetry system produced results much more comparable to those from the laboratory test than did the direct wired system.

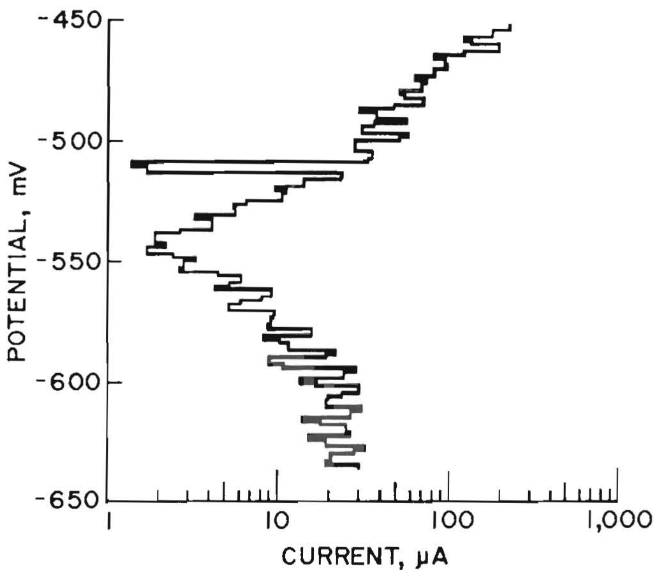


FIGURE 23.—Potential-current data for wrought steel obtained in an iron ore mill using the telemetry system.

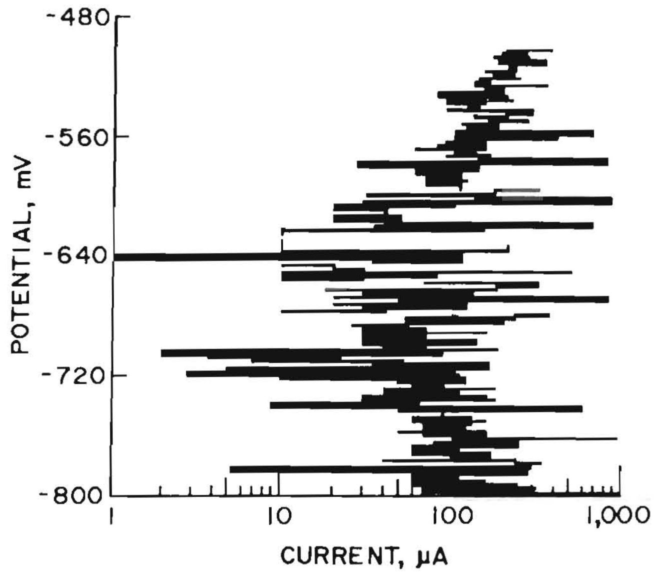


FIGURE 24.—Potential-current data for wrought steel in a copper ore mill using a direct wired system.

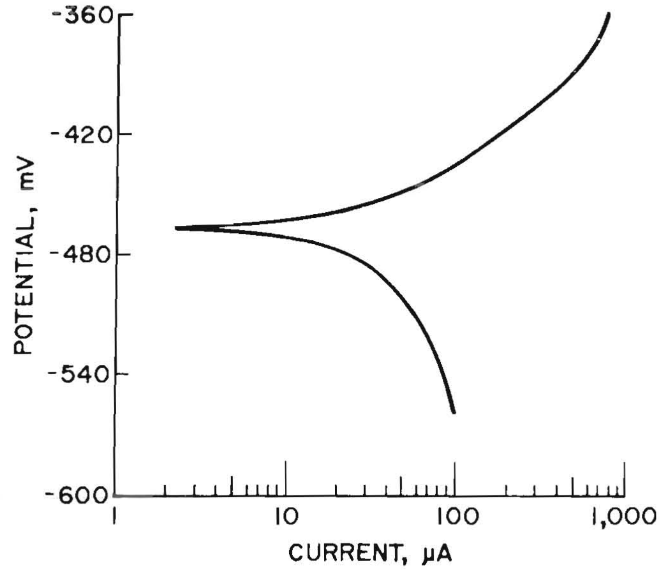


FIGURE 25.—Potential-circuit data for wrought steel obtained in a laboratory test simulating iron ore mill conditions.

CONCLUSIONS

All objectives of the field test campaign were met. The feasibility of constructing portable test equipment and operating it in a commercial plant was demonstrated. Application of modern solid-state electronics technology, including electronic instead of mechanical switching systems, allowed the size, weight, and power requirement for the instrumentation system to be minimized. The advantages of amplifying the digitizing signals as close to the source as possible were clearly demonstrated. Use of radio transmission techniques was shown to be reliable. The application of mathematical data processing methods such as FFT filtering remains to be seen, but the data obtained by the telemetry system would seem to be more amenable to these methods than that from the direct wired analog system, based on relative amounts of scatter.

In summary, the use of digital signal processing techniques and telemetry methods is clearly advantageous over the use of more conventional systems, and the development of two-way systems that allow process control as well as monitoring seems entirely feasible.

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U.S. GOVERNMENT PRINTING OFFICE: 1988 — 547-000/80,033